Direct Numerical Simulation (DNS) of Heat and Mass Transfer in a Fluidized Bed

Zhi-Gang Feng, Samuel Musong, Miguel Ponton, Steven Cooks, and Adam Roig

Department of Mechanical Engineering, University of Texas at San Antonio

Abstract

A Direct Numerical Simulation (DNS) method has been developed and used for studying heat and mass transfer of 225 to 1204 heated spheres in a fluidized bed. By exploring the rich data generated from the DNS, we are able to obtain statistically averaged fluid and particle velocities as well as the overall heat transfer rate in the bed. Good agreement between the current study and the one by Pan et al. (2002) is found for the hydrodynamic properties of the bed such as pressure gradients within the bed and the relationship between fluidization velocity and bed solid fraction. The particle-averaged Nusselt number is found to increase as the fluidization velocity increases and the bed height rises; particles at the entrance of the bed tend to have maximum heat transfer rate because of higher particle-fluid temperature gradients in this region; as the fluid moves upward in the bed it gets warmer, which reduces particle-fluid temperature gradients and decreases the transfer rate of particles.

Introduction

Fluidization involves a fluid flow that is supplied through a bed of solid particles at a sufficient velocity such that the entire suspension of solid particles behaves like a fluid. Because of enhanced particle-fluid heat transfer and chemical reaction rates in fluidized beds, fluidization is used in applications such as chemical reactors, coal combustion, and fluid catalytic cracking. The challenge with the experimentally measured values of the heat transfer coefficients in general is the low accuracy in-bed temperature measurements and oversimplifications in the flow models. Usually, temperature measurements taken in beds with thermocouples have been interpreted very differently and direct measurements of solid particle temperatures are even more difficult and unreliable. Numerical modeling can be a vital technique that is suitable to approximate the local and average heat transfer coefficient of a fluidized bed. DNS is a Lagrangian-Eulerian method that provides detailed fluid velocity and particle motion. It is applied to study the fluidization of hundreds of spheres in a fluidized bed.

Numerical Methods

Consider spherical particles of constant temperature immersed in an incompressible Newtonian fluid. To determine the momentum and heat transfer exchanges between particles and fluid, we have to resolve the fluid field and particle motions. The modified momentum equations with the Boussinesq approximation in dimensionless form may be written as follows:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \bullet \vec{\nabla}\vec{u} = -\vec{\nabla}p + \frac{1}{Re}\nabla^2\vec{u} + \frac{Gr}{Re^2}T\hat{e}_g + \vec{f}$$

The modified energy balance equation:

$$\frac{\partial T}{\partial t} + \vec{u} \bullet \vec{\nabla}T = \frac{1}{Pr\,Re}\nabla^2 T + \lambda$$

Equation of translational motion:

$$(\rho_r - 1)V_p\frac{d\vec{U}_i}{dt} = \int_{V_p}\vec{f}\,dV + (\rho_r - 1)V_p\vec{g} + \vec{F}_i^{col}$$

Equation of rotational motion:

$$\frac{I_p}{\rho_r}(\rho_r - 1)V_p\frac{d\vec{\omega}_i}{dt} = -\int_{V_p}(\vec{x} - \vec{x}_i)\times\vec{f}\,dV + \vec{T}_i^{col}$$

Particle temperature is assumed constant.

u, U	velocity
t	time variable
p	fluid pressure
Re	Reynolds number
Gr	Grashof number
T	temperature
$\mathbf{e}_g$	unit vector in the direction of gravity
f	force density function
Pr	Prandtl number
Pe	Peclet number
λ	heat density function
ρ_r	particle and fluid density ratio
Vp	particle volume
F^{col}	particle collision force
I_p	moment of inertia
ω	particle angular velocity
x	particle position vector
T^{col}	torque exerted onto the particle due to collision

Results and Discussion

Hydrodynamics of A Fluidized Bed

We study the fluidization of 225 to 1204 spheres at different Reynolds numbers. The DNS allows us to obtain flow velocity as well as the dynamics of each individual sphere. Fig. 1 shows the velocity magnitude contours in a fluidized bed after flows become steady.

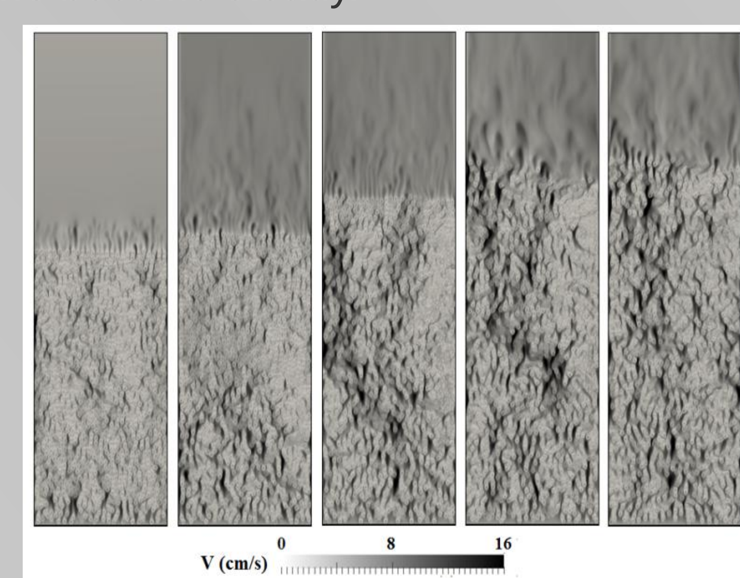


Fig.1: Fluidization of 1204 spheres at five different velocities.

Using statistical averaging, we are able to compute both the particle and fluid-particle mixture velocity profiles in a bed, as shown in Fig. 2

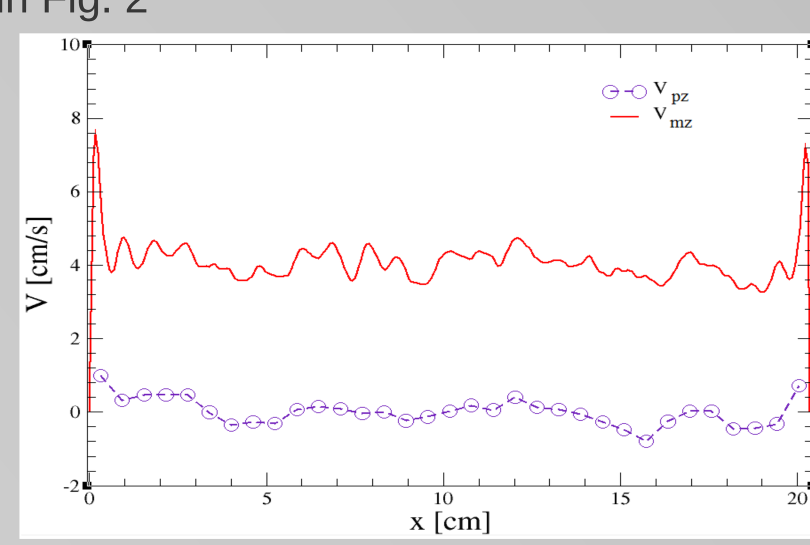


Fig. 2: time and z-direction averaged particle velocity and mixture velocity

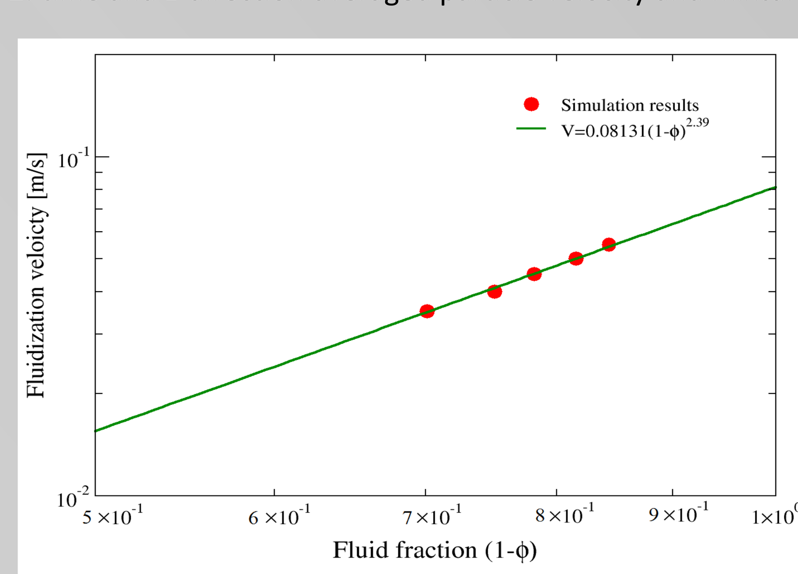


Fig. 3: The fluidization velocity vs. fluid fraction plotted in a log-log plot.

A relationship between the fluidization velocity and fluid fraction, as predicted by the celebrated Richardson and Zaki correlation, is able to be recovered, as shown in Fig. 3 .

Heat Transfer in A Fluidized Bed

We first validate the DNS by studying the forced convective heat transfer on a sphere and compare results with those found in the literature.

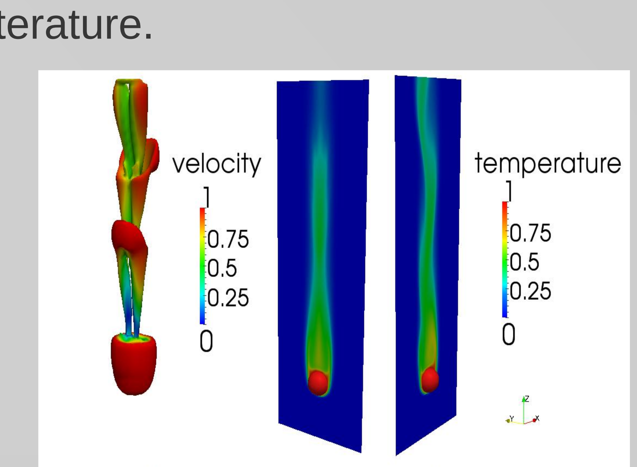


Fig.4: Flow vortical structures (left) and temperature contours at Re=350.

Fig.4 shows flow vortical structures at Re=350. It is seen that periodically vortex loops or hairpins are shed from the surface of the sphere, which is consistent with the vortical structures observed by other researchers.

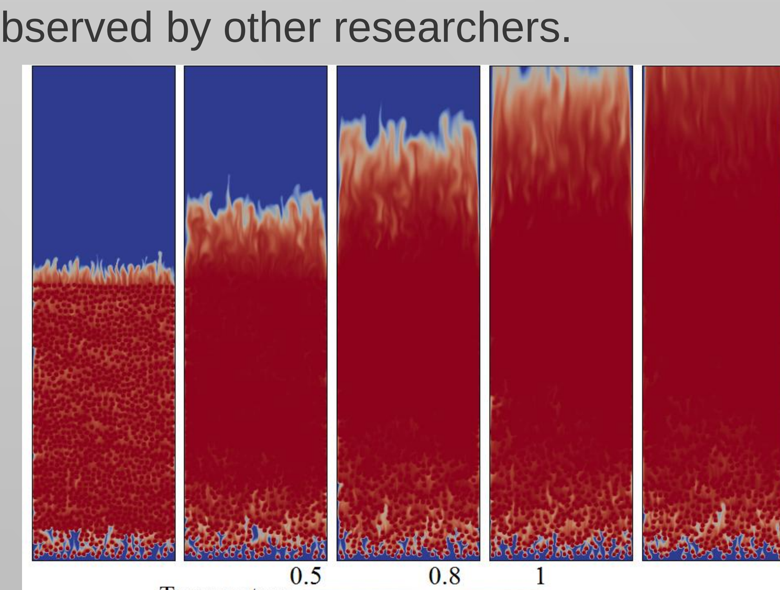


Fig. 5: Snapshots of temperature contours in a fluidized bed when V=4 cm/s. From left to right: t = 1s, 3s, 5s, 7s, and 10s

The fluid velocity and temperature fields are solved simultaneously. Fig. 5 shows the snapshots of temperature field in the fluidized bed. The heat transfer rates between spheres and fluid can be computed accurately using the resolved temperature field. It is found that spheres near the entrance of the bed have the highest heat transfer rate. The average heat transfer rate or Nusselt number can be determined at various flow conditions, as shown in Fig. 6.

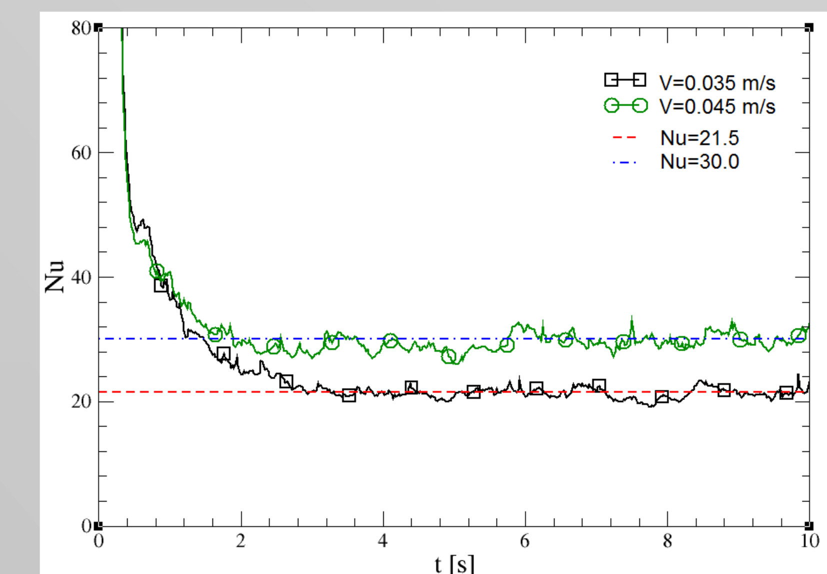
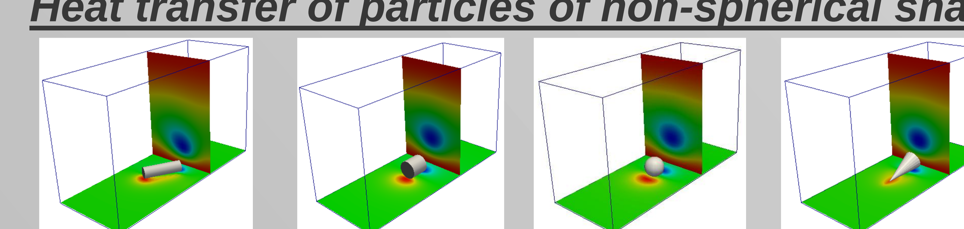


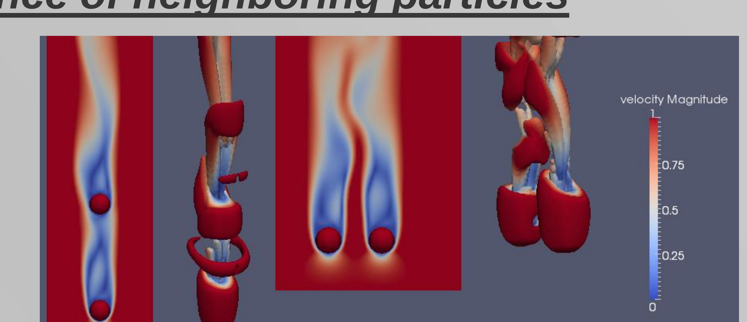
Fig. 6: Average Nusselt number of particles in a fluidized bed vs. time

Future Work

Heat transfer of particles of non-spherical shape.



Influence of neighboring particles



Conclusions

The DNS-IB method has been applied to study heat transfer of spheres in a fluidized bed. Detailed flow velocity, pressure, and temperature fields for the fluidization of 225 to 1204 spheres in a narrow channel are obtained at five different fluidization velocities. The average Nusselt number based on all the spheres, which can be used to compute the total heat transfer rate between the spheres and fluid, is found to increase with the increase of fluidization velocity. The hydrodynamics properties of the bed, such as the bed height, the solid fraction, and the wall pressure gradient, agree very well with the study of Pan et al. (2002). A straight line log-log plot is also observed, as predicted by the cerebrated correlation of Richardson and Zaki (1954).

Students Participated

Graduate Students:
Miguel Cortina (PhD candidate), Adams Roig, Cenk Sarikaya, Steven Cooks, Samuel Musong,
Undergraduate Students:
Silvia Murguia and Carlos Mendez

Papers Published

1. Feng, Z-G., Ponton, M. E. C., Michaelides, E. E., and Mao, S. (2014). "Using the Direct Numerical Simulation to Compute the Slip Boundary Condition of the Solid Phase in Two-Fluid Model Simulations." *Powder Technology.* j.powtec.2014.01.020
2. Feng, Z.G. (2014), "Direct Numerical Simulation of Forced Convective Heat Transfer from a Heated Rotating Sphere in Laminar Flows," ASME *J. of Heat Transfer, " Journal of Heat Transfer*. doi:10.1115/1.4026307
3. Feng, Z-G and Musong, S. (2014), "Direct Numerical Simulation of Heat and Mass Transfer of Spheres in a Fluidized Bed," *Powder Technology*. 262C:62-70.
4. Musong, S. and Feng, Z-G (2014), "Mixed Convective Heat Transfer from a Heated Sphere at An Arbitrary Incident Flow Angle in Laminar Flows." *Int. Heat and Mass Transfer.* In revision.
5. Feng, Z-G and Roig, A, "Direct numerical simulation of particle heat and mass transfer in a fluidized bed." ASME Gas-Solid Symposium, 2014, Chicago.
6. Feng, Z-G, Musong, S., and Michaelides, E. E., "A three dimensional immersed boundary method for free convection from single spheres and aggregates." ASME Gas-Solid Symposium, 2014, Chicago.

Acknowledgements

This work was supported by a grant from DOE through the National Energy Technology Laboratory (Grant number DE-FE0011453; Mr. Steven Seachman, project manager).